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CHARACTERIZATION OF MODE I PROPERTIES OF FULL-DEPTH Z-FIBER STUBBLE IN CO-BONDED COMPOSITES (PREPRINT)

Stephen B. Clay

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Structures Division

APRIL 2007

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14. ABSTRACT

Z-pins are small-diameter carbon rods that are ultrasonically inserted through composite laminates in the z-direction to provide extra resistance to crack growth and delamination. They are normally inserted through co-cured composites, but this paper presents an experimental study on a new z-pin stubble manufacturing technique that is compatible with the co-bonding process. Stubble lengths were 0.125 and 0.250 inch. Double cantilever beam (DCB) specimens were used to characterize the effect of stubble diameter and height on the Mode I crack resistance. It was determined that the new approach using a second ultrasonic step is indeed necessary for stubble heights on the order of 0.125 inch. It was also found that increasing the stubble height from 0.04 inch to 0.125 inch resulted in a much more significant improvement in Mode I properties than increasing the aerial density from 2 % to 4 %. Finally, taking that final step of increasing the stubble height from 0.125 to 0.250 inch did not improve the properties as much as would be expected from previous studies.

15. SUBJECT TERMS

z-pins, z-fiber, stubble, double cantilever beam, mode I, composites, through-thickness reinforcement

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Characterization of Mode I Properties of Full-Depth Z-Fiber™ Stubble in Co-bonded Composites

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Z-pins are small diameter carbon rods that are ultrasonically inserted through composite laminates in the z-direction to provide extra resistance to crack growth and delamination. They are normally inserted through co-cured composites, but this paper presents an experimental study on a new z-pin stubble manufacturing technique that is compatible with the co-bonding process. Z-pin stubble is created by inserting pins through the thickness of an uncured laminate and trimming the pins to a certain height above the surface. After initial cure, another uncured composite part is cured on the exposed stubble. Early researchers were limited to an exposed stubble height of 0.030 inch, which would not provide all of the benefits of a full-depth co-cured z-pin reinforced joint. Past studies have successfully increased the useful stubble reinforcement to 0.080 inch which was shown to have significant advantages. This paper describes a study in which the stubble lengths were increased to 0.125 and 0.250 inches. Double cantilever beam (DCB) specimens were used to characterize the effect of stubble diameter and height on the Mode I crack resistance. It was determined that the new approach using a second ultrasonic step is indeed necessary for stubble heights on the order of 0.125 inches. It was also found that increasing the stubble height from 0.040 inches to 0.125 inches resulted in a much more significant improvement in Mode I properties than increasing the aerial density from 2% to 4%. Finally, taking that final step of increasing the stubble height from 0.125 to 0.250 inches did not improve the properties as much as would be expected from previous studies.

Nomenclature

AFRL	=	Air Force Research Laboratory
ASTM	=	American Society for Testing and Materials
AW	=	aerial weight
DCB	=	double cantilever beam
E_{11}^F	=	flexural modulus
E_{33}	=	transverse modulus
G_{13}	=	transverse shear modulus
G_{ic}	=	critical energy release rate
in-lb/sq in	=	inch pounds per square inch
lb	=	pounds
in	=	inches
psi	=	pounds per square inch
UT	=	ultrasonic

I. Introduction

For the most part, composite aircraft structures are currently joined using mechanical fasteners. In order to eliminate the need for drilling holes and installing fasteners, some aircraft manufacturers have recently begun production of composite parts using alternative joining approaches like z-pinning and stitching. Z-pins, shown in Figure 1, are small carbon rods that are ultrasonically inserted through uncured laminates in the z-direction to improve resistance to crack growth [1-2]. Z-pins have been successfully used in the co-curing process, but cannot be used effectively in the co-bonding process. The Air Force Research Laboratory (AFRL) has conducted research into furthering the use of z-pins in co-bonded joints through a process using a new stubble approach. Z-pin stubble is made by inserting pins through both an uncured laminate and a sacrificial material on the surface of the laminate. After cure, the sacrificial material is removed, leaving stubble exposed from the surface. Next, another uncured composite substrate is seated on the stubble using a novel second stage ultrasonic step. This additional step allows longer and denser z-pins to be used in the co-bonding process. This study is a continuation of previous research conducted by AFRL [3-4] during which a method to fabricate 0.125 inch long stubble using rubber sheet materials was developed. This paper presents an extension of this approach to include 0.250 inch long stubble and to characterize the Mode I properties of co-bonded composite joints with both 0.125 and 0.250 inch long stubble.

II. Materials and Manufacturing

The new process of using two separate steps of ultrasonic joining to create stubble reinforced joints was described in a previous effort [3]. During the current study, stubble trials were conducted with 0.020 inch diameter z-pins to determine the effect of 0.125 inch and 0.250 inch long z-pin stubble and 2% and 4% stubble aerial densities on the Mode I crack resistance. Commercial strength neoprene was used as the sacrificial material to create the z-pin stubble fields since a previous study showed that it exhibited excellent performance at a relatively low cost. The z-pins that were used had a diameter of 0.020 inch and original lengths of 0.475 and 0.875 inches. A typical pin is shown in Figure 1.

Figure 1. Photograph of 0.020 inch diameter Z-Fiber ™.

Each side of the double cantilever beam (DCB) specimen was fabricated from 28 zero degree plies of AS4/3501-6 graphite epoxy prepreg tape (300 AW). Each specimen was a total of ten inches long, one inch wide, and 0.6 inches thick. The initial four inch crack length was created by placing a 0.0005 inch thick sheet of Teflon in the mid plane of the specimen as shown in Figure 2. Since a smooth rubber sheet was used to create the z-pin stubble field, the stubble surface was grit blasted with glass beads and thoroughly rinsed with acetone after the first cure cycle to provide an appropriate surface for co-bonding the second composite.

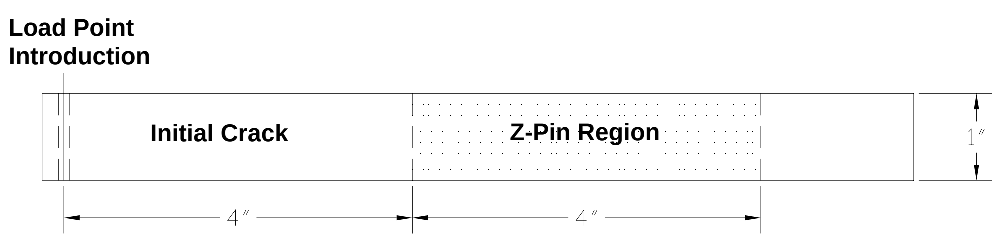


Figure 2. Schematic of Double Cantilever Beam Specimen.

To achieve co-cured panels equivalent to 0.125 and 0.250 inch long co-bonded stubble, twelve inch by twelve inch sub-panels were assembled to the appropriate z-pin thicknesses (0.250 and 0.500 inches) with Teflon at the mid-plane as a crack-starter. Z-pins were then ultrasonically inserted through the entire thickness of the sub-panels which resulted in z-pins on each side of the mid-plane of lengths 0.125 and 0.250 inches. After the z-pins were inserted, additional plies were added to each side of the z-pinned panel to achieve the desired thickness of the specimen of 0.600 inches. This approach was successful in obtaining co-cured panels with z-pins of appropriate length on each side of the mid-plane. A schematic of the side-view of the co-cured specimen that is equivalent to the 0.125 inch long stubble specimen can be seen in Figure 3.

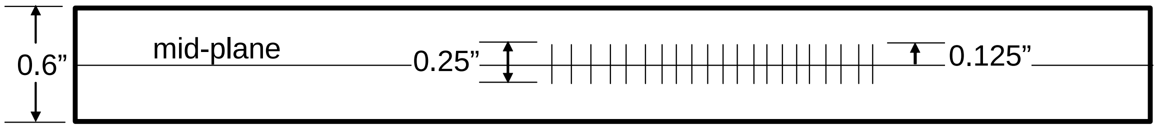
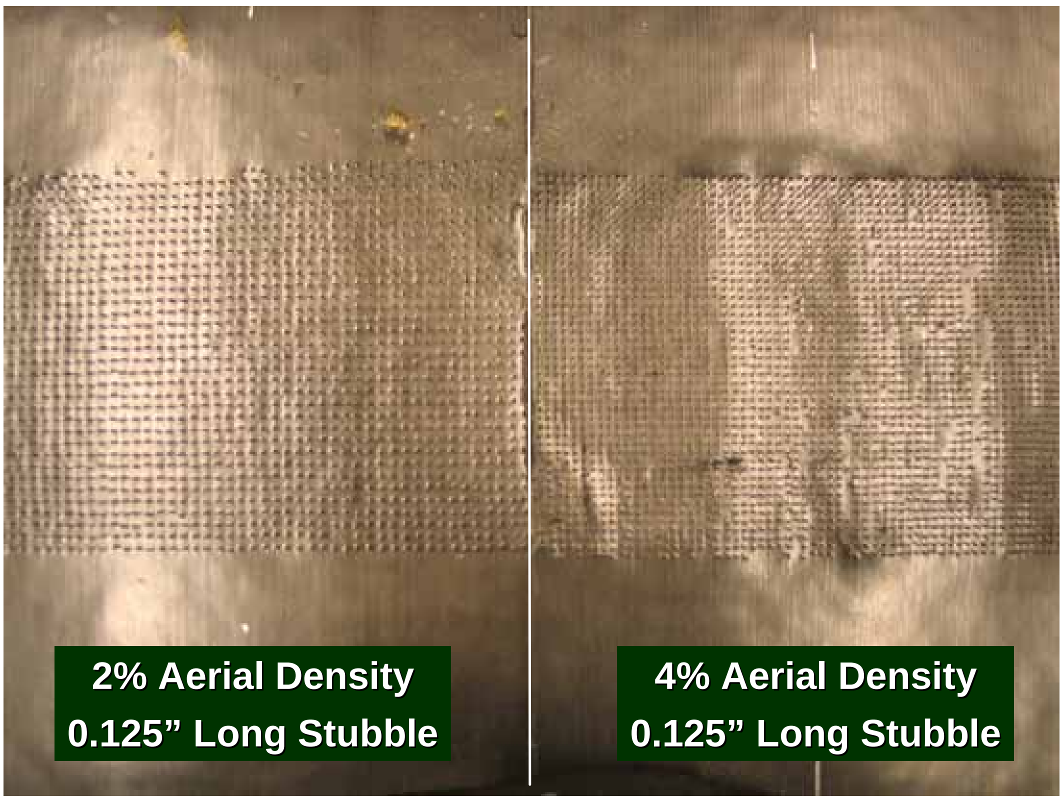


Figure 3: Schematic of Co-cured Z-pinned Baseline Specimen

Previous research studies resulted in an effective manufacturing procedure for 0.125 inch long stubble using 0.125 inch thick commercial strength neoprene. Figure 4a shows a photograph of the successful fabrication of the 0.125 inch long stubble during the current study. Unfortunately, the 0.250 inch thick neoprene that was used to create 0.250 inch long stubble was difficult to remove in portions of the panel as shown in Figure 4b. As a result, only two specimens were extracted from the 0.250 inch stubble panel near the center where the neoprene came off cleanly. The portion of the panel with the neoprene residue was scrapped.



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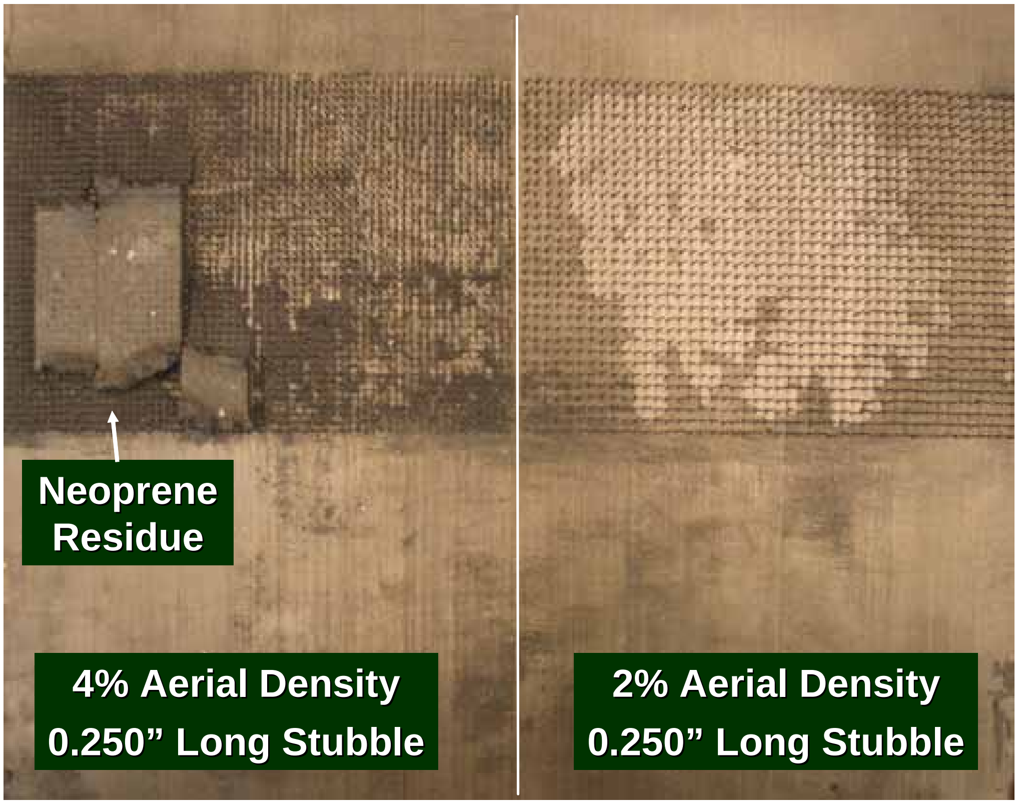


(b)

Figure 4: Photograph of 12” X 12” Stubble Panels after 1st Cure Cycle (a) 0.125” stubble (b) 0.250” stubble

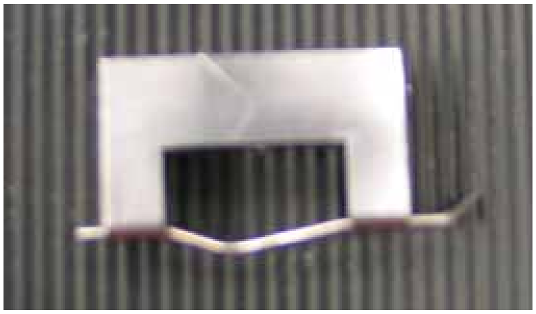
III. Experimental Details and Data Reduction

As mentioned above, DCB stubble experiments were conducted to increase the correlation range between stubble length and delamination resistance. The test matrix included both 0.125 and 0.250 inch long stubble as well as 2 and 4% aerial densities. The entire test matrix is shown in Table 1.

After the DCB specimens were fabricated they were tested on a screw driven universal testing machine according to a modified ASTM D5528-94a procedure [5]. The specimen is fixed onto the testing machine using a pin fixture, securing the specimen through the drilled holes. It was found that the strength of the existing pin fixture was insufficient for the longer stubble fields. The loading pin and clevis both experienced permanent deformation due to the excessive loads during DCB testing of the 0.125 and 0.250 inch z-pin stubble specimens as shown in Figure 5a. The fixture was redesigned to accommodate the higher loads as shown in Figure 5b. A second modification was done to more evenly distribute the load on the center plies of the DCB specimens (Figure 5c).

Table 1. DCB Test Matrix.

Aerial Density (%)	2nd Ultrasonic Step	Stubble Height (in)
2	Yes	0.125
2	Yes	0.250
2	No	0.125
2	No	0.250
4	Yes	0.125
4	Yes	0.250
4	No	0.125
4	No	0.250
2	Co-cured (baseline)	0.125
2	Co-cured (baseline)	0.250
4	Co-cured (baseline)	0.125
4	Co-cured (baseline)	0.250



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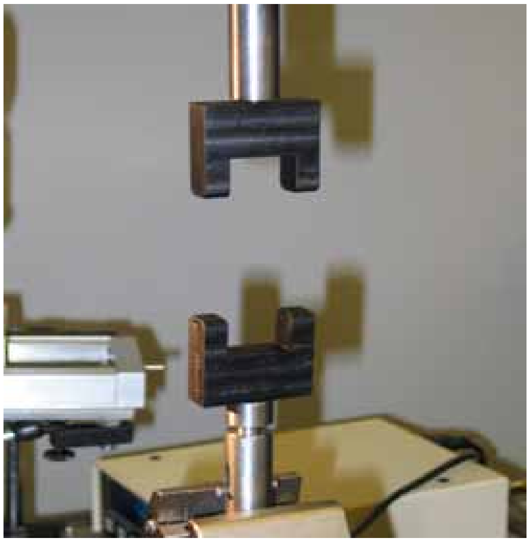


(b)

(c)

Figure 5: DCB Test Fixture (a) original failed fixture, (b) first mod, and (c) second mod

Using the new fixture, the specimens were loaded at 0.04 inches/minute until the crack grew to 0.25 inch at which point the loading rate was increased to 0.2 inches/minute (Figure 6). A microscope was used to observe the crack initiation and its progression through the joint. A modified beam theory[6] was used to analyze the fracture properties, while the critical energy release rate for initiation ($G_{ic\ initiation}$) was defined by the initial non-linearity in the energy release rate versus crack length curve. An average energy release rate value was determined for each specimen based on the area method. Table 2 shows some of the input properties for the modified beam theory analysis. These values were obtained from experimental results using AS4/3501-6 laminates and from the open literature.

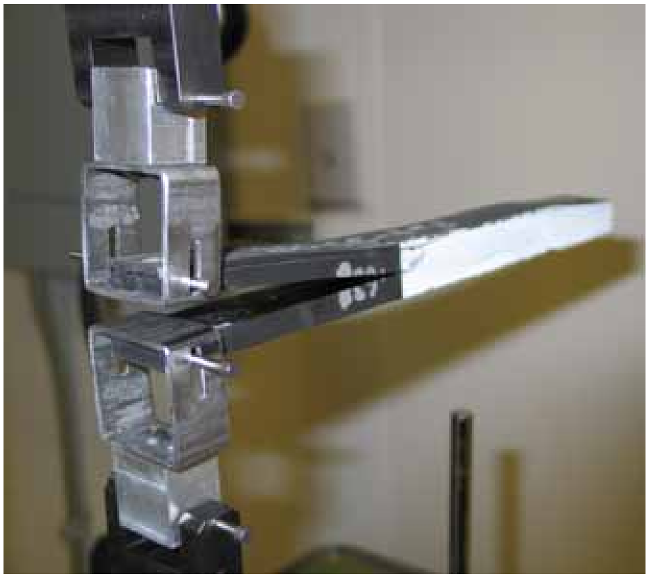


Figure 6: Photograph of DCB Specimen in Pin-Loaded Fixture

Table 2. Input Properties for Modified Beam Theory Analysis.

	Unidirectional AS4/3501-6
$\mathbf{E_{11}^F}$	20.4×10^6 psi
$\mathbf{E_{33}}$	1.49×10^6 psi
$\mathbf{G_{13}}$	0.85×10^6 psi

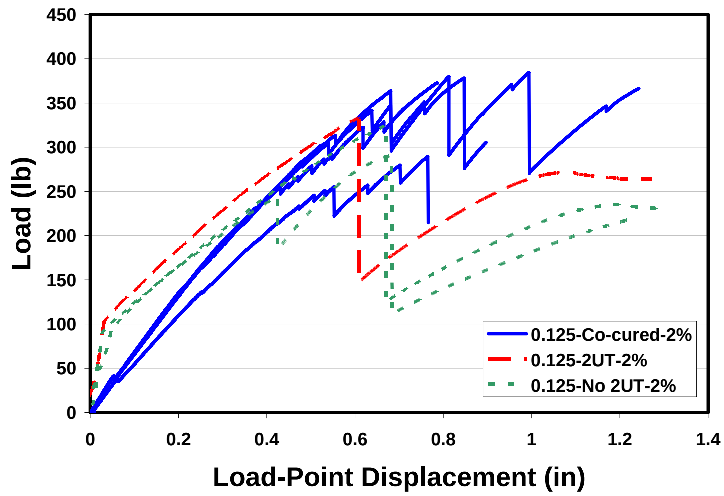
IV. Results

The primary purpose of the current research project is to determine the effect of “full-depth” co-bonded z-pin stubble reinforced composites on the Mode I properties. Double cantilever beam tests were performed on 0.125 and 0.250 inch long stubble specimens. Manufacturing and testing trials were performed on specimens that were fabricated both with and without the second ultrasonic step. The specimens without the second ultrasonic step relied totally on the autoclave heat and pressure to seat the second composite on the z-pin stubble. Figure 7 shows a photograph of a typical 0.250 inch long stubble specimen without the second ultrasonic step. The gap at the joint indicates that the specimen did not achieve 100% compaction during the cure.

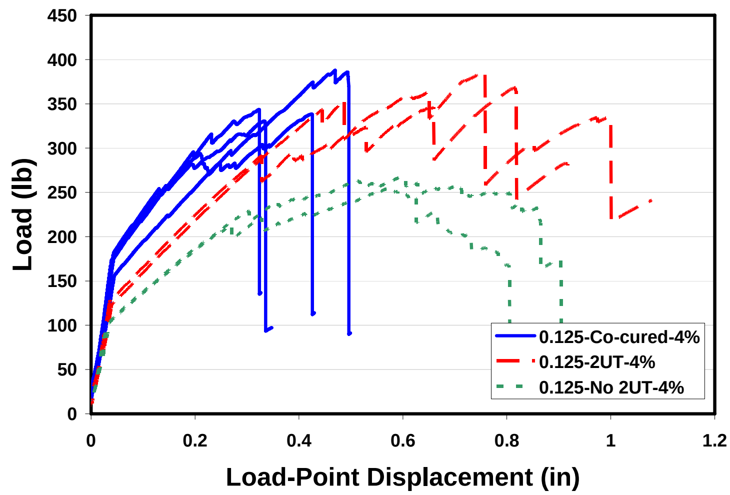
Figure 7: Photograph of 0.125 inch Stubble Specimen Without 2nd Ultrasonic Step

Figure 8 compares the Mode I loading characteristics of co-cured z-pinned composites to 0.125 inch long stubble reinforced composites. The specimens with (red-dashed line) and without (green-dotted line) the new second ultrasonic step are shown. For the 2% aerial density shown in Figure (a), it can be seen that the overall maximum load achieved for the three variants all fall in approximately the same range of 300 to 380 lb, but the co-cured specimens generally reached a slightly higher load. Another observation is that after the first major load drop, the co-cured specimens experienced four to five repeated load cycles on the order of 50 to 100 lb, while the stubble reinforced specimens experienced a single larger load drop of 150 to 200 lb. This behavior indicates that the co-cured specimens tended to fail one row of pins at a time, but the stubble specimens failed multiple rows simultaneously.

For the 4% aerial density shown in Figure (b), it can be seen that the overall maximum load achieved for both the co-cured and the stubble reinforced specimens with the second ultrasonic step fall in approximately the same range of 300 to 400 lb, but the stubble specimens without the second ultrasonic step only achieved on the order of 250 lb. Also, after the first major load drop, the stubble specimens with the second ultrasonic step experienced four to five repeated load cycles on the order of 50 to 100 lb, while the co-cured specimens experienced a single larger load drop of 150 to 200 lb. Finally, it should also be noted that the stubble specimens without the second ultrasonic step did not experience the usual zig-zag loading characteristics since they did not fail at the mid-plane. The failure initiated at the gap due to non-compaction and continued to grow interlaminarly above the z-pins.



(a)

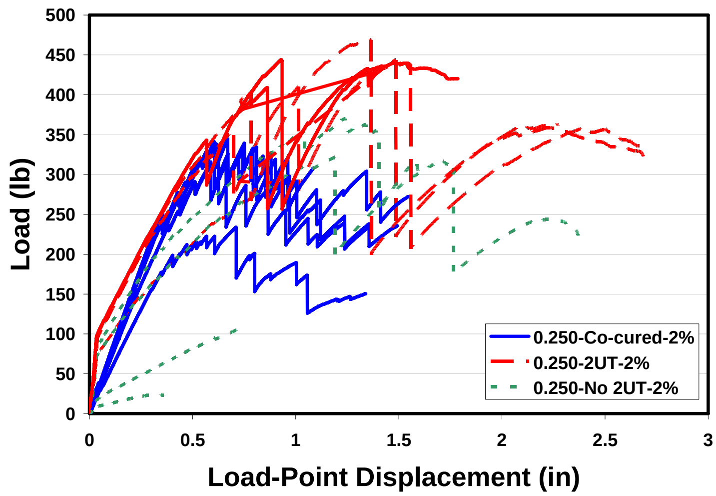


(b)

Figure 8: Effect of Manufacturing Process on the Mode I Load-Carrying Capability of 0.125 inch Stubble Reinforced Composite DCB specimens - (a) 2% (b) 4%

Figure 9 displays the equivalent data as Figure 8 but for 0.250 inch long stubble instead of 0.125 inch long stubble. The 2% aerial density results shown in Figure (a) qualitatively indicate that the stubble reinforced composites with the second ultrasonic step achieved the highest loads (400 – 450 lb) during Mode I loading. The co-cured z-pinned composites and half of the stubble reinforced composites without the second ultrasonic step failed at approximately 300 to 350 lb, while the other half of the stubble specimens without the second ultrasonic step failed at very low loads. These failures can be attributed to the large gap in the joint shown in Figure 7.

For the 4% aerial density shown in Figure (b), it should first be noted that only one specimen for each stubble variant is shown due to the fabrication issue with the neoprene mentioned previously and shown in Figure 4. It can be seen that the co-cured z-pinned specimens achieved the highest maximum loads on the order of 350 to 600 lb, but that there is relatively high scatter in the data. The stubble specimen with the second ultrasonic step achieved the second highest load of approximately 400 lb, while the specimen without the second step reached only 300 lb.



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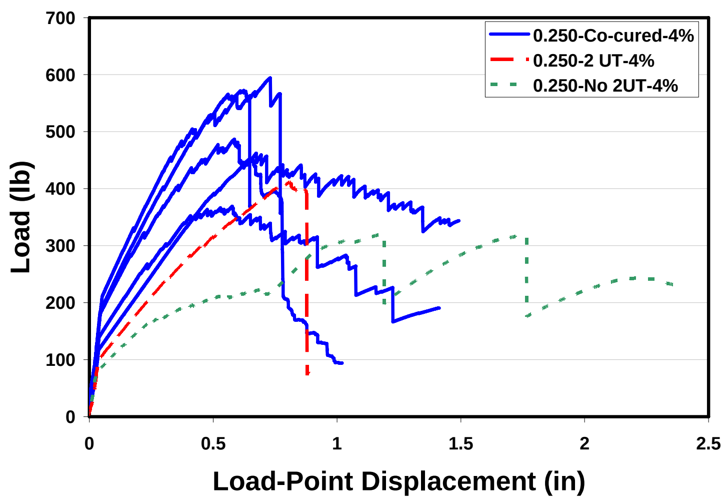
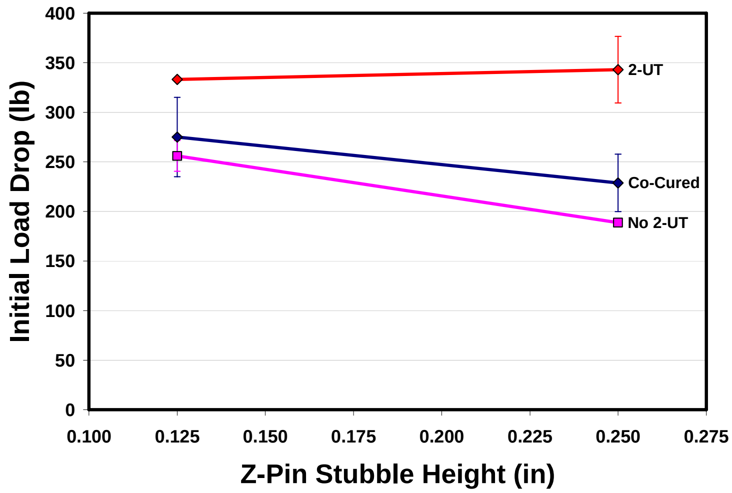


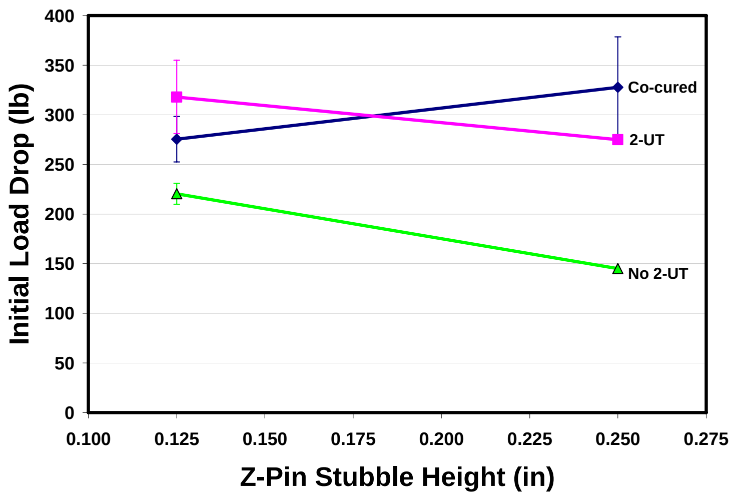
(b)

Figure 9: Effect of Manufacturing Process on the Mode I Load-Carrying Capability of 0.250 inch Stubble Reinforced Composite DCB specimens - (a) 2% (b) 4%

Another piece of data that was collected for each test was the initial load drop. The initial load drop was defined as the point at which the load first decreased a minimum of ten pounds. Figure 10 displays these results for the (a) 2% and (b) 4% aerial density as a function of stubble height. The error bars show one standard deviation. For the 2% aerial density, Figure (a) shows that the stubble specimens with the second step achieved the highest loads before the initial failure while the other two variants experienced initial failure at lower loads. Of even more interest are the 4% aerial density results. Figure (b) indicates that the co-cured and stubble specimens with the second step experienced initial failure at approximately the same loads (250 to 350 lb), but the specimens without the second step experienced the first load drop 100 to 200 lb sooner. This is another result of the poor consolidation achieved by autoclave heat and pressure during cure.



(a)



(b)

Figure 10: Effect of 2^{nd} Ultrasonic Step on Initial Mode I Load Drop at (a) 2% and (b) 4% Aerial Density

Figure 11 compares the maximum Mode I loading results of the current study with the results of the previous efforts during which shorter stubble lengths were characterized. The data shown in Figure 11 only include the specimens that were fabricated using the second ultrasonic step. The error bars show one standard deviation of the data.

The first observation is that the baseline specimen with no z-pins achieved a maximum load of only about 35 lb. It is obvious that the z-pin stubble in the joint significantly improves the Mode I load carrying capability of composites. Next, the effect of aerial density was minimal. Increasing the aerial density from 2% (dark blue) to 4% (magenta) only increased the maximum load carrying capability by approximately 50 lb. On the contrary, increasing the stubble length significantly increased the Mode I properties. Going from a stubble height of 0.040 inches to a stubble height of 0.125 inches increased the maximum load by approximately 300 lb. The conclusion is that significant benefits in crack resistance will be realized up to z-pin embedded depths of 0.125 inches. Finally, a knee in the curve was discovered around 0.125 inches. Doubling the stubble height from 0.125 inches to 0.250 inches only increased the maximum load by 50 to 100 lb. Considering the difficulty in fabricating the 0.250 inch stubble, the small increase in load carrying capability is probably not worth the extra effort.

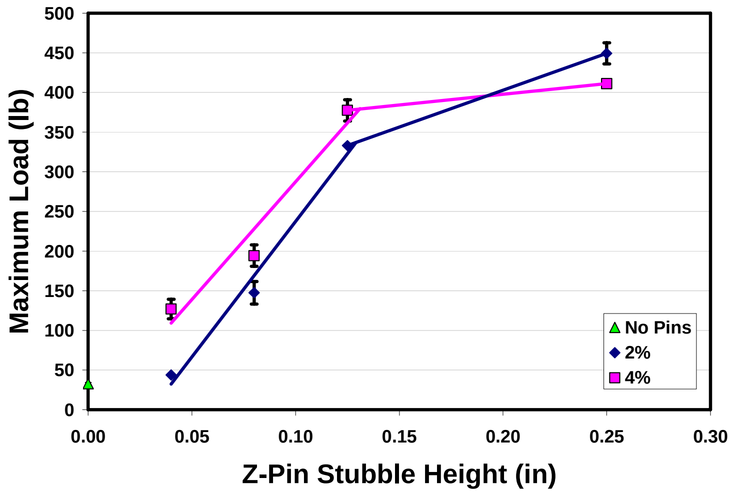


Figure 11: Effect of Stubble Height and Aerial Density on the Maximum Mode I Load-Carrying Capability

Finally, the critical energy release rates were determined for the stubble reinforced composites. A modified beam theory [6] was used to analyze the fracture properties, while an average energy release rate value was determined based on the area method. Figure 12 shows the results of the current study (0.125 and 0.250 inch stubble) compared to the previous efforts (0.040 and 0.080 inch stubble). The average energy release rate provides a toughness metric for the joint that generally describes its resistance to crack growth over an extended distance (1 to 3 inches). First, it is apparent that the baseline specimens with no z-pins have extremely low values for average G. The failure of the baseline specimen was catastrophic, so once the crack started to grow there was very little resistance to continued growth and very little enclosed area under the load displacement curve. Next, similar to the maximum load data, the value added by increasing the aerial density from 2% to 4% is only about 10 in-lb/sq in, but increasing the stubble height significantly improves the joint toughness. For the 2% specimens, increasing the stubble height from 0.040 inches to 0.250 inches increase the average G from 10 to 90 in-lb/sq in. A similar trend was seen in the 4% specimens up to a stubble height of 0.125 inches, but increasing the stubble height of the 4% specimens to 0.250 inches created a situation of failure above the pins resulting in low toughness.

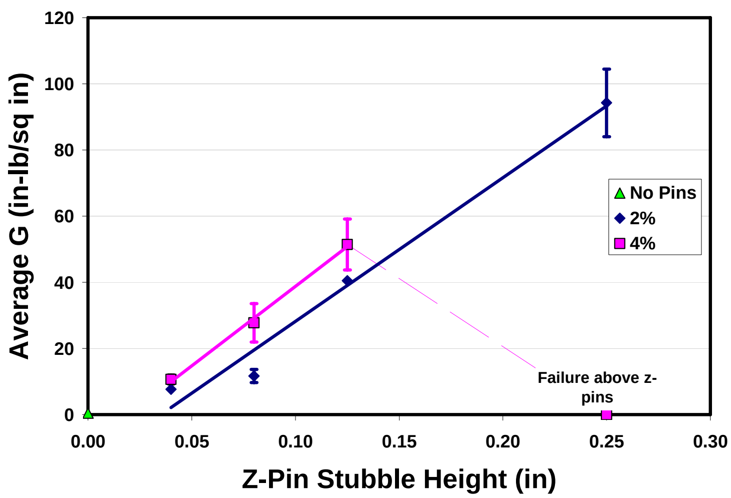


Figure 12: Effect of Stubble Height and Aerial Density on the Average Apparent Mode I Energy Release Rate (Area Method)

V. Conclusions and Recommendations

The ultimate goal of this research study was to determine the effect of long, dense z-pin stubble on the Mode I properties. The fabrication of the specimens using the new approach with commercial strength neoprene was completely successful for the 0.125 inch long stubble, but only partially successful for the 0.250 inch stubble. One recommendation would be to use two separate layers of 0.125 inch thick neoprene instead of one layer of 0.250 inch thick neoprene. This would likely result in the complete removal of the rubber without leaving any residue.

The results of the DCB test for the longer, denser stubble indicate a variety of things. First, the second ultrasonic step in the fabrication process is very important, especially for the longer, denser stubble fields. Without it, the specimens do not achieve good compaction and fail at lower loads. The 0.125 inch long stubble with 2% aerial density z-pins might be satisfactory without the second step, but any configuration longer or denser should definitely use the second step.

Second, it was shown that z-pin stubble significantly increases the maximum Mode I load carrying capability. The stubble height played a more important role in improving the performance than the aerial density. Also, a knee in the curve was found at 0.125 inch long stubble, indicating a decreased significance in going from 0.125 inches to 0.250 inches.

Finally, the toughness of the joint as defined by the area method was significantly improved with the addition of z-pin stubble. Similar to the maximum load, increasing the aerial density did not improve the toughness as much as increasing the stubble height. It was also determined that the failure mode of the 0.250 inch stubble specimen with 4% aerial density changed from crack propagation through the mid-plane to interlaminar failure above the z-pins.

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